

Near opposition photometry of comet C/2007 N3 (Lulin)

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ABSTRACT

Observations on comet C/2007 N3 (Lulin) were made at phase angles close to opposition ($1.7^\circ - 10^\circ$). Photometric observations were carried out during 2009 February 24–28, in the IHW blue and red continuum and R broad band using photo-polarimeter mounted on the 1.2m telescope at Mt Abu IR Observatory. In all the bands, a significant linear increase in brightness with decreasing phase angle is detected for the above phase angle range. The phase coefficient ($\beta = 0.040 \pm 0.001 \text{ mag deg}^{-1}$ estimated in IHW red (6840\AA) filter band) is found to be independent of wavelength. No non-linear opposition surge is observed for phase angle $> 1.7^\circ$. The linear increase in brightness with decreasing phase angle in the range mentioned earlier can be explained using the shadow hiding model. The colour of the comet is found to be similar to the solar colour indicating the dominance of grains larger than $0.1\mu\text{m}$. A dip in the brightness of about 0.20 mag is seen at the phase angle $\sim 6.5^\circ$.

Key words: Comets – photometry – dust scattering – comets - individual – Comet C/2007 N3 (Lulin)

1 INTRODUCTION

Comet C/2007 N3 (Lulin) was discovered as an asteroidal object by Quanzhi Ye on images acquired by Chi Sheng Lin in the course of the Lulin Sky Survey and later Young reported it showing marginal cometary appearance on CCD images taken with the Table Mountain 0.61-m telescope (Ye 2007). In February 2009 comet was not only closest to the Earth but it happened to be close to the opposition. It has been observed that in the region within a few degrees of zero phase angle, the reflectance of many Solar system bodies and also of particulate samples measured in the laboratory increases non-linearly as the phase angle decreases (see Hapke 1993, for a review). This is known as “the opposition effect” (Gehrels 1956). The first attempt to explain the opposition effect was offered as a consequence of the reduction of mutual shadows cast between regolith grains as phase angle decreases (see Hapke 1963, 1986). However, this hypothesis fails to explain the strong opposition effect observed in highly reflecting media (see Harris et al. 1989; Brown & Cruikshank 1983). An alternative explanation of the opposition surges in highly reflecting media was offered by Shkuratov (1985), Muinonen & Lumme (1990), and Hapke (1990) invoking the hypothesis of coherent constructive interference, also called coherent backscattering. Hapke (1993, 1998) applied it to explain the opposition surge in lunar samples. The coherent backscattering has also been invoked to explain the reflectance and backscattering of Saturn’s ring (Mishchenko 1992a,b; Mishchenko & Dlugach 1992; Horn et al. 1996).

It would be interesting to investigate if comets show opposition surge when observed in near back scattering geometry. There have been attempts in the past to observe the opposition surge in comets (e.g. Meech & Jewitt 1987; Kiselev & Chernova 1981; A’Hearn et al. 1984; Millis et al. 1982). Though Kiselev & Chernova (1981); A’Hearn et al. (1984); Millis et al. (1982) have reported enhanced backscattering in comets P/Ashbrook-Jackson, Bowell(1982I), and P/Stephan-Oterma respectively, Meech & Jewitt (1987) re-analyzed the data and found no opposition surge greater than $\sim 20\%$; instead a small linear phase coefficient ranging $0.02 - 0.04 \text{ mag deg}^{-1}$ for the phase angle $< 30^\circ$ is estimated. Delahodde et al. (2001) have studied the phase function of nucleus of comet 28P/Neujmin 1 covering $\alpha = 0.6 - 14.5^\circ$ and have reported a phase trend with opposition surge.

Comet C/2007 N3 (Lulin), which was near opposition during our observing run (i.e. February 24–28), presented an opportunity to investigate opposition effect. However, the comet C/2007 N3 (Lulin) happened to be close to opposition i.e. phase angle (Sun-Comet-Earth angle α reaching 0°) at \sim UT 08:00 February 26, 2009 (local day time), by the time we could begin observation on February 26, comet’s phase angle had increased to 1.7° . The comet was bright enough to carry out high S/N photometric observations and in this communication we present the results based on the photometric observations on comet C/2007 N3 (Lulin) during February 24–28, 2009 when phase angle ranged from 1.7° to 10° .

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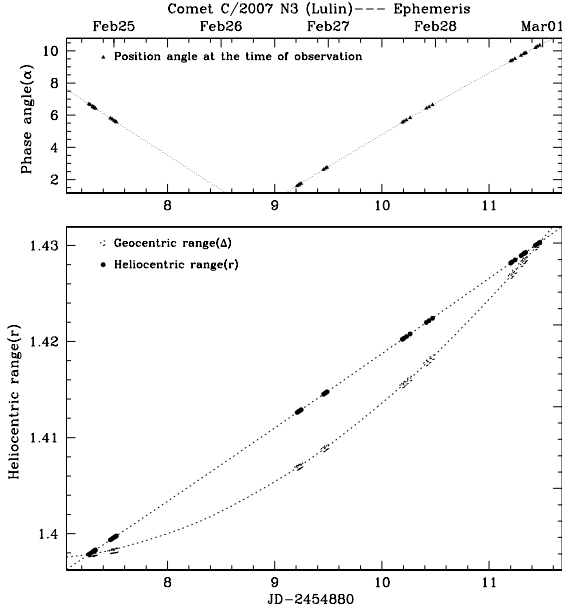


Figure 1. Upper panel: Change in phase angles (α) with time during the observing run. Lower panel: Change in heliocentric range(r) and geocentric range (Δ). r and Δ at the time of observation are marked. Julian date in x-axis is abbreviated as JD.

2 OBSERVATIONS AND ANALYSIS

Photometric observations of comet C/2007 N3 (Lulin) were made during the period February 24–28, 2009 with a two channel photo-polarimeter (Deshpande et al. 1985; Joshi et al. 1987), mounted on the 1.2m telescope of Mt. Abu IR Observatory (MIRO) operated by the Physical Research Laboratory (PRL), Ahmedabad. The instrument is equipped with IAU’s International Halley Watch (IHW) continuum filters (3650/80Å(UC), 4845/65Å(BC), 6840/90Å(RC)) (Osborn et al. 1990) and broad band filter R ($\lambda = 6400\text{Å}$; $\Delta\lambda = 1580\text{Å}$). We have been regularly using the IHW filters for observations of comets (Joshi et al. 1987; Sen et al. 1991; Ganesh et al. 1998; Joshi et al. 2002, 2003; Ganesh et al. 2009; Joshi et al. 2010) and every time before the use we check their characteristics. Using the same filter set facilitates comparing different comet’s data observed by us.

Most of the observations were made with aperture 26'' (corresponding to projected diameter of 7770 km on February 24); however on February 24 some observations were made with aperture 54'' (projected diameter 16150 km). In addition to the observations with IHW filters, we also made observations with R band filter using different apertures - 10'', 20'', 26'' and 54'' (projected diameter varying from ~ 3000 km to 16000 km (see Table 1)) to study the brightness as a function of radial distance from the comet nucleus. All the observations were made under dark sky conditions, comet being more than 3 magnitudes brighter than the sky. Nonetheless, to take care of the sky brightness, observations were made alternately centered on the photo center of the comet and on a region of the sky more than 30 arcmin away from the comet (along the anti-tail direction). The comet magnitudes were calculated after subtracting sky brightness. Observed comet magnitudes were converted to standard system using the observations of solar type stars HD88725, HD76151.

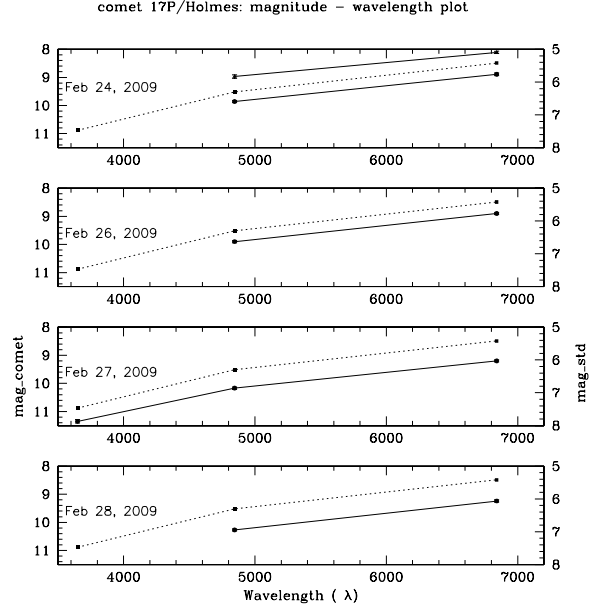


Figure 2. Spectral energy distribution as observed through different apertures on different dates. Observed magnitude of comet is plotted against the mean wavelength of the filter band. Filled triangle and filled circle represent the data observed through 54'' and 26'' apertures respectively and open square is for the solar analogue (HD 76151). Error bars $\pm 1\sigma$ (< 0.05 mag), lie within the symbols used.

3 RESULTS & DISCUSSION

The observation log with comet parameters and our results is given in Table 1. The entries include date, JDT (=JD - 2454880), RA & Dec, Heliocentric(r) & Geocentric(Δ) distances, phase angle(α), aperture used, projected diameter, filter, total integration time and magnitude. The observed magnitudes reported here were corrected for extinction and then converted to the standard magnitude system using the observations of the solar analogs. To estimate instrumental magnitude, several observations of shorter integration time (say 40 sec in R-band and 200 sec in narrow bands) were taken and then average value of magnitude and its statistical error were calculated. Details of the observing procedure are same as discussed in Joshi et al. (2010). The error in magnitude listed in Table 1 is the total error which includes observational error, error in atmospheric extinction and the error due to the transformation of magnitude to standard system.

Figure 1 shows r , Δ and α at the time of observation taken from the HORIZONS ephemeris (Giorgini et al. 1997). The comet was closest to the Earth on February 24, 2009 ($\Delta = 0.41$ AU & with 26'' aperture the projected diameter of comet is 7700 km). The sampled area projected on the comet is not large enough to average out the small scale inhomogeneities. There might be a possibility of BC band being contaminated by the C_2 emission band lying close to it. To address this possibility, we looked at the spectra provided by Buil (private communication)¹ for February 22, 2009 (the nearest date to our observing run), and notice that C_2 emission band close to the BC (4845Å) band partly overlaps with it. The upper limit of contamination of the BC band by this feature is

¹ see his web-site <http://www.astrosurf.com/buil/>

Table 1. Photometric observations of comet Lulin C/2007 N3. Listed entries are Date, JDT (=JD-2454880, where JD represent Julian date), right ascension(RA) and declination(Dec) of the comet at the time of observation, Heliocentric range(r), Geocentric range(Δ), phase angle(α), aperture("), projected diameter on comet, filter, total integration time(IT) and magnitude.

Date	JDT	RA(H:M:S)	Dec($^{\circ}$ ' ")	r (AU)	Δ (AU)	α°	Ap(arcsec)	ProDia(km)	Fil	IT(sec)	mag
Feb 24	7.26686	11:7:8	5:42:9	1.39784	0.411934	6.69049	26	7768	6840	360	8.91 \pm 0.04
	7.27789	11:6:55	5:43:26	1.39792	0.411955	6.64204	26	7768	4845	600	9.89 \pm 0.03
	7.30027	11:6:29	5:46:1	1.39809	0.411998	6.54373	26	7769	R	120	9.05 \pm 0.03
	7.30578	11:6:22	5:46:39	1.39813	0.412009	6.51953	20	5976	R	120	9.40 \pm 0.03
	7.31339	11:6:14	5:47:32	1.39819	0.412024	6.48614	13	3885	R	150	9.81 \pm 0.03
	7.32004	11:6:6	5:48:18	1.39824	0.412036	6.45691	10	2988	R	150	10.13 \pm 0.03
	7.32810	11:5:57	5:49:14	1.3983	0.412052	6.42153	54	16138	R	150	8.35 \pm 0.03
	7.46641	11:3:16	6:5:14	1.39934	0.412319	5.81402	26	7775	R	200	8.99 \pm 0.03
	7.48224	11:2:58	6:7:4	1.39946	0.41235	5.74453	26	7776	6840	1000	8.87 \pm 0.03
	7.50100	11:2:36	6:9:14	1.3996	0.412386	5.66213	26	7776	4845	1000	9.82 \pm 0.03
	7.51507	11:2:20	6:10:52	1.3997	0.412413	5.60032	54	16152	6840	300	8.11 \pm 0.03
	7.52227	11:2:11	6:11:42	1.39976	0.412427	5.5687	54	16153	4845	300	8.89 \pm 0.05
	9.19308	10:30:2	9:18:10	1.41272	0.422649	1.66324	26	7970	6840	180	8.88 \pm 0.03
	9.20926	10:30:18	9:16:39	1.41261	0.422524	1.6026	26	7968	6840	1400	8.88 \pm 0.03
Feb 26	9.23272	10:29:52	9:19:6	1.41279	0.422726	1.69999	26	7971	4845	1200	9.88 \pm 0.03
	9.24727	10:29:35	9:20:36	1.4129	0.422853	1.76037	26	7974	R	240	9.03 \pm 0.03
	9.45573	10:25:43	9:42:2	1.41451	0.424776	2.62004	26	8010	R	280	9.05 \pm 0.03
	9.47419	10:25:22	9:43:54	1.41466	0.424956	2.6955	26	8013	4845	800	9.92 \pm 0.04
	9.48810	10:25:7	9:45:19	1.41476	0.425092	2.75236	26	8016	6840	800	8.93 \pm 0.04
	10.19096	10:12:24	10:54:44	1.42023	0.432589	5.5499	26	8157	R	240	9.25 \pm 0.03
	10.20660	10:12:7	10:56:14	1.42035	0.432772	5.61133	26	8161	6840	1200	9.08 \pm 0.03
	10.22891	10:11:43	10:58:22	1.42052	0.433034	5.699	26	8166	4845	1400	10.08 \pm 0.03
	10.26322	10:11:6	11:1:38	1.42079	0.433442	5.83363	26	8173	3650	3200	11.17 \pm 0.03
	10.41472	10:8:24	11:15:53	1.42198	0.435305	6.42402	26	8209	R	240	9.26 \pm 0.03
Feb 28	10.43958	10:7:57	11:18:12	1.42217	0.43562	6.52009	26	8215	4845	2600	10.33 \pm 0.04
	10.47126	10:7:22	11:21:16	1.42243	0.436043	6.64736	26	8222	6840	1400	9.32 \pm 0.03
	11.20142	9:54:46	12:26:31	1.42817	0.445986	9.36405	26	8410	R	240	9.41 \pm 0.03
	11.21471	9:54:33	12:27:39	1.42828	0.44618	9.41268	26	8414	6840	1200	9.24 \pm 0.03
	11.24145	9:54:5	12:29:57	1.42849	0.446574	9.51046	26	8421	4845	2000	10.27 \pm 0.03
	11.29839	9:53:7	12:34:48	1.42894	0.447422	9.71799	26	8437	4845	2000	10.28 \pm 0.03
	11.32226	9:52:43	12:36:50	1.42913	0.447781	9.80471	26	8444	R	400	9.44 \pm 0.03
	11.33268	9:52:32	12:37:43	1.42921	0.447939	9.84251	20	6498	R	280	9.81 \pm 0.03
	11.34157	9:52:23	12:38:28	1.42928	0.448074	9.87468	10	3250	R	320	10.58 \pm 0.03
	11.43195	9:50:51	12:46:3	1.43	0.449463	10.2002	26	8476	R	840	9.51 \pm 0.03
	11.45084	9:50:32	12:47:37	1.43015	0.449757	10.2677	26	8481	R	800	9.59 \pm 0.03
	11.47224	9:50:11	12:49:24	1.43032	0.450092	10.3441	20	6529	R	400	10.09 \pm 0.03

estimated to be $< 10\%$. The colour of the comet, as discussed in section 3.1, is close to the solar colour. This supports the view that the contamination of comet's BC magnitude due to the neighboring C_2 emission band is negligible. Also the comet's heliocentric distance has not changed significantly during the observing run to affect the above inference.

3.1 Spectral Energy Distribution and the Phase Curve

Figure 2 shows the continuum energy distribution of C/2007 N3 (Lulin). In this figure observed magnitudes are plotted against the mean wavelength of the filter band. For comparison, energy distribution of solar analogue star HD76151, which was observed during the observing run, is also plotted. It is seen that during the observing run the comet colour is similar to that of the solar colour. On February 24 the comet is observed through two apertures: 26" and 54" (projected diameter 7700 km and 16300 km respectively). There is indication that comet colour through the larger aperture is slightly bluer. This could be due to the disintegration of larger grains into smaller grains as they move out resulting in higher population of sub-micron size grains in the outer coma. Observations on all the dates with 26" aperture show comet colour similar to

solar colour.

In the following we discuss the light curve and the phase curve of the comet. For this purpose, magnitudes, denoted as $m(1, 1, \alpha)$, are referred to at Δ and r equal to 1AU by subtracting the term $2.5\text{Log}(\Delta r^2)$ from the observed magnitudes. The light curves (LCs i.e. $m(1, 1, \alpha)$ vs time(JD)) of C/2007 N3 (Lulin) are plotted in Figure 3(a) and the phase angles at the time of observation are marked. LCs in different filter bands are annotated in the figure. It is seen that comet gets brighter as α decreases. During the pre-opposition phase we have observations only at two phase angles - 6.69 and 5.75 $^{\circ}$, with the comet being brighter at lower phase angle. The phase curve is better covered during the post-opposition phase, the minimum phase angle, at which observations are made, being $\sim 1.7^{\circ}$. The comet was not observable when it was close to zero phase (local day time). During post-opposition phase, a clear increase in brightness with decreasing α is observed. This is consistent in all the filter bands. To look at the change in brightness with phase, we have plotted $m(1, 1, \alpha)$ vs α in Figure 3(b). No opposition surge is noticed for the observed range in α , only some linear increase of brightness with decreasing α is detected. We checked for the linearity in phase curve by plotting the flux against the phase

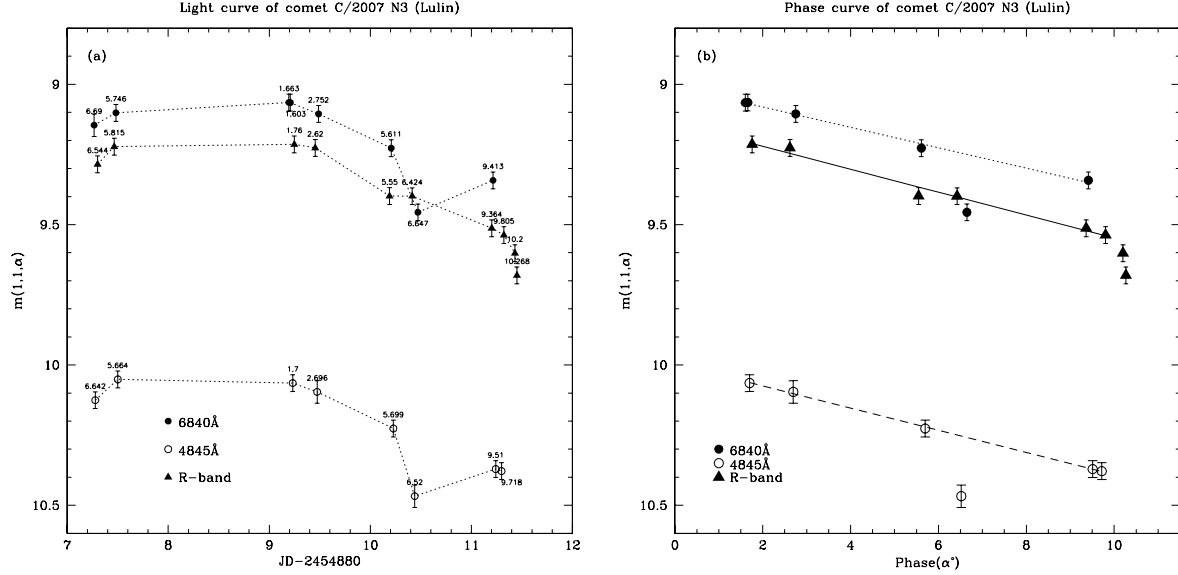


Figure 3. (a) Light curve showing variation of IHW and R magnitudes through $26''$ aperture normalized to $\Delta = 1\text{AU}$, $r=1\text{AU}$ with time(JD - 2454880). (b) Normalized magnitude plotted against post opposition phase angle. Error bars ($\pm\sigma$) are plotted.

angle and found it to be linear in all the bands. For discussion purpose in this paper we have adopted the phase curve (magnitude vs phase) i.e. Figure 3(b). Though we notice a linear brightness increase with decreasing α for $1.7^\circ < \alpha < 10^\circ$, we do not have observations for $\alpha < 1.7^\circ$ to comment on opposition surge (i.e. any non-linear increase in brightness) as α approaches zero degree.

Phase curve shows one interesting feature - at phase angle near 6.5° the brightness shows a decrease in BC and RC bands. As there are no observations (including the R band) between phase angle 6.4 and 9.4° , it is difficult to comment on the actual trend. The phase curve in R band shows a sudden decrease in brightness at phase angle $> 10^\circ$ but unfortunately we do not have data in BC and RC in this range to make a comparison. As discussed earlier, the sampled area projected on the comet is not large enough to average out the small scale inhomogeneities which might cause fluctuations in the brightness. However, with the present data it is difficult to quantify this.

We have estimated the phase coefficient (i.e. slope of the phase curves) ignoring the dip, discussed in the previous paragraph. The estimated slopes in 4845Å, 6840Å and R -bands are respectively 0.036 ± 0.002 , 0.040 ± 0.001 and $0.041 \pm 0.003 \text{ mag deg}^{-1}$. Within the estimated error, the phase coefficients in all the filter bands might be taken same i.e. the phase coefficient is independent of the wavelength. The shadow hiding model can explain this kind of brightening of the comet with decreasing phase angle. Meech & Jewitt (1987) have reported similar results on some other comets studied by earlier researchers (see section 1). However, the phase coefficient in the present case is slightly higher than the values reported by Meech & Jewitt (1987). Though Delahodde et al. (2001) have reported a phase trend with opposition surge ($\alpha = 0.6 - 14.5^\circ$) in case of the nucleus of comet 28P/Neujmin 1, it is very likely that comet nucleus surface behaves differently (similar to asteroids) than the dust particles in the coma.

3.2 Radial Profile of the brightness

As mentioned earlier in section 2, we have made observations in R -band through various apertures ($10''$, $20''$, $30''$ & $54''$) to study behaviour of the comet brightness with distance from the photocenter. Radial profile of brightness in R -band is plotted in Figure 4 for February 24 and 28. The procedure of getting the radial distribution of the brightness is the same as described in our earlier papers (Ganesh et al. 2009; Joshi et al. 2010). On February 24 brightness drops at a distance of $\sim 2000\text{km}$. As the sampled area on comet is not large, the possibility of observing inhomogeneous projected area can not be ruled out. Later, on February 28 the brightness distribution is smooth apart from a slight depression beyond 2000 km .

4 CONCLUSIONS

The following conclusions are drawn from the present study on Comet C/2007 N3(Lulin).

- (i) Colour of the comet is similar to the solar colour indicating the grain size larger than $0.1\mu\text{m}$.
- (ii) Significant brightness enhancement with decreasing phase angle is observed. The phase coefficient, β , is found to be $0.040 \pm 0.001 \text{ mag deg}^{-1}$ which is independent of the wavelength. These findings support shadow hiding model to explain the increase in brightness with decreasing phase angle.
- (iii) A dip of $\sim 0.20 \text{ mag}$ in the brightness at the phase angle $\sim 6.5^\circ$ is observed in the continuum narrow bands which might be due to presence of inhomogeneities in the coma.
- (iv) Brightness drops smoothly radially outward apart from a slight depression near 2000km , especially on February 24.

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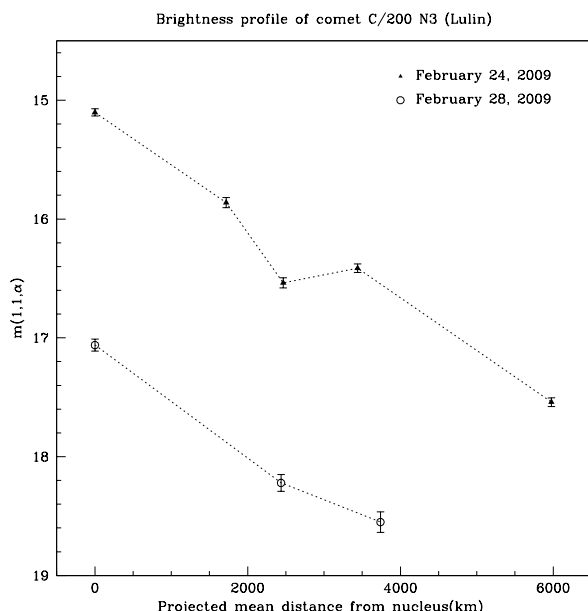


Figure 4. Radial brightness variation as observed on February 24 and 28, 2009. Error bars are $\pm\sigma$.

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